◉ 速報硏究論文

A Study on the Method for Calculating the Reliability of Diesel Engines in Operation

A.N. Sobolenko* · C.H. Woo** · W.K. Wang***

디젤 기관의 운전 신뢰성 계산 방법에 관한 연구

아나톨리 쇼보랭코* · 우 종호** · 왕 우경***

Key words : Diesel engine, Reliability, Theoretical model, Distribution function

요 약

디젤 기관의 신뢰성 평가는 일반적으로 운전중에 발생한 사고 내용을 통계 처리하여 평가하기 때문에, 운전자가 사전에 사고 발생을 예견하여 적절한 시기에 예방 정비를 한다든지, 기관의 상태에 따른 최적 운전 조건을 파악하여 기관을 안전하게 운전하는데 어려움이 있다. 또한, 디젤 기관을 새로이 개발한다든지 설계 변경을 할 경우, 기관의 신뢰성을 평가하는데도 상당한 어려움이 있다.

본 논문에서는 선박용 주기관으로 사용되는 디젤 기관을 대상으로 하여, 디젤 기관의 운전 상태에 따른 운전 신뢰성을 예측할 수 있는 프로그램을 개발하였으며, 예측 결과를 실험 결과와 비교 · 검토하였다.

Symbols and Abbreviations

$\overline{N}$	: the relative load of an engine
α	: the parameter of β – distribution
β	: the parameter of β – distribution
$\overline{N}_c$	: the relative load of an engine cylinder
$\overline{\sigma}_{Nc}$	: the mean square deviation of the relative load of an engine cylinder
$\Psi(\overline{N}_c)$	: the distribution density of an engine cylinder relative to the load deviation
$f(\overline{N})$	: the distribution density of the engines relative load
$T_{C\max}$	: the maximum temperature of a cylinder
T_{C1PR}	: the temperature of the cylinder in the area of the first piston ring
$\sigma_{\theta\max}$	: the maximum amount of stress, leading to vertical cracks in the cylinder
σ_y	: the axial stress causing horizontal cracks

* The Far Eastern State University of Fishing and Economy, Dept. of Marine Propulsion Plant, Vladivostok, Russia.
** Pukyong National University, Dept. of Computer Engineering, Pusan, Korea. (receipt : '98. 3.)
*** Yosu National University, Faculty of Training Ship, Yosu, Korea.

	in the cylinder
σ_{max}	: the maximum stress on the cooled surface causing cracks in the cylinder cover
$f_S(S)$	: the distribution density of a load
$f_R(R)$	: the distribution density of bearing ability
$\Psi(y)$	: the distribution function of casual value y
$f(\Psi(y))$	: the reverse function of function $\Psi(y)$
χ^2	: the criteria of Pirson
$\overline{t}$	: the relative frequency of distribution

1. Introduction

The existing methods of evaluating the reliability of engines are based on the collection of statistical data relating to operational failures. They do not permit the evaluation of the potential reliability of a new engine design, the reliability of an engine after its modernization, or the reliability of an engine when its conditions of operation have been changed.

The reliability of engines is evaluated on the basis of the probability of the destruction of its parts under normal operating conditions. The loads and the sustaining ability of the engine parts are therefore presented as casual quantities. It is necessary to know the probable characteristics of the parameters of a load and to calculate interesting value as a function of these parameters. The load of parts, in turn, depends on the mode of an engine load in operation and its technical condition.

The modes of a main engine load and their cylinders are represented as a function of the set of consistent casually distributed effects on the vessel, the engine and its elements. The following factors should be taken into consideration: the modes of operation of a vessel and the engine' s technical condition. Besides the quality of adjustment of an engine renders influence to a mode of separate cylinders load.

The distribution of a load of the main engines of marine vessels is casual quantity, which can be described by the known laws of distribution. The widespread normal distribution was calculated by a mathematical model, based on a hypothesis about the normal laws of distribution. However such calculations do not always reflect the features of the main ship engine' s operation, with its dispersion of loads. This creates a situation in which there are limits to the application of the distribution law, with resulting asymmetry.

2. Theoretical Analysis

The analysis which follows examines the distribution of the loads of the main engines of six types of motor ship. The use of representative samples for each type of ship yields a probability of account $P \geq 0.99$ while the margin of potential error is 0.05. The theoretical and empirical laws of distribution of each load were compared using the criteria of Pirson and for each load that of Kolmogorov.

When the analysis of the loads is defined as representing as a rule, asymmetric distributions, the best approximation is a β-distribution with density of the kind described:

$$f(\overline{N}, \alpha, \beta) = \frac{(\alpha+\beta+1)!}{\alpha!\beta!}\overline{N}^{\alpha}(1-\overline{N})^{\beta} \quad (1)$$

Factorials of nonintegral significance may be found by applying the approximate formulas:

$$\alpha! \cong \alpha^{\alpha}\exp(-\alpha)\sqrt{2\pi\alpha}\ ; \quad \beta! \cong \beta^{\beta}\exp(-\beta)\sqrt{2\pi\beta} \quad (2)$$

A comparison of the empirical and theoretical laws of distribution shows that in accordance with the criteria of Pirson, the hypothesis about a β-distribution is valid with a probability of error of the first kind of less than 0.005. In contrast, the hypothesis about normal distribution is invalid with a degree of error greater than 0.2 for three of the six types of ships.

A β-distribution using the criteria of Kolmogorov proves to be from 5~15 % less than for the normal distribution for all the types of ship examined. These results confirm to follow the accepted model of the distribution of the loads of main ship diesels.

Equation (1) does not tell us anything about the character of distribution of the load of each cylinder. This is because there is non-uniformity in the distribution among the cylinders, which depends on the technical conditions of an engine. An approximation of the distribution laws of load deviations among cylinders concerning the average received from the data of the main engines in operation is undertaken. The results are characterized by normal distribution, the density of which is described thus:

$$\Psi(\overline{N}_C)=\frac{1}{\sqrt{2\pi}\,\bar{\sigma}_{\overline{N}C}}\exp\left[-\frac{(\overline{N}_C-\overline{N})^2}{2\bar{\sigma}^2_{\overline{N}C}}\right] \qquad (3)$$

The function of the load distribution of each cylinder is represented in the two-size space under formulas (1) and (3).

The function of the distribution in a one-size space may be obtained using the formula of complete probability:

$$P_i=P_{\overline{N}}P_{\overline{N}C}^{(\overline{N})} \qquad (4)$$

where $P_{\overline{N}C}^{(\overline{N})}=\Psi(\overline{N}_C)\,d\,\overline{N}_C$, the probability of a fixed load deviation. Its significance among cylinders is in the range of $\overline{N}_C$ to $(\overline{N}_C+\Delta\overline{N}_C)$, $P_{\overline{N}}=f(\overline{N})\,d\,\overline{N}$ is the probability that the load of an engine ranges from $\overline{N}$ to $\overline{N}+\Delta\overline{N}$.

The mathematical model of the cylinder load distribution of the low speed main engines is then described by the formula:

$$f(\overline{N}_C)=f(\overline{N})\int_0^1\Psi(\overline{N}_C)\,d\,\overline{N}_C \qquad (5)$$

For the low speed main engines of the transport vessels, the mathematical model of the load distribution of the cylinders is described by the formula:

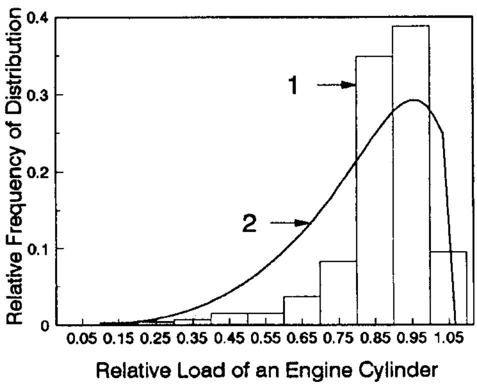
$$f(\overline{N}_C)=\frac{1}{\sqrt{2\pi}\,\bar{\sigma}_{\overline{N}C}}\frac{(\alpha+\beta+1)!}{\alpha!\beta!}\overline{N}^{\alpha}(1-\overline{N})^{\beta}\int_0^1\exp\left[-\frac{(\overline{N}_C-\overline{N})}{2\bar{\sigma}^2_{\overline{N}C}}\right]d\,\overline{N}_C \qquad (6)$$

A comparison of the theoretical laws of distribution computed using both model (6) and empirical methods – on the statistical data has shown that according to the criteria of Pirson, the convergence is 99.5 % accurate (fig. 1).

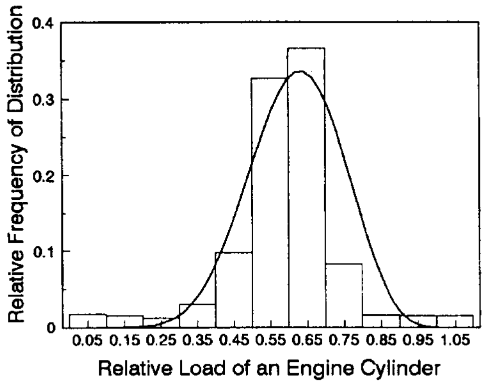
The load of cylinders of an engine influences first the reliability of the parts of the cylinder piston assembly. Thus it is often the case that the group of parts of the main engine of a new ship series begins to fail in operation.

One typical failure of the low speed main engines is the failure of the parts of the cylinder piston assembly. These failures are the most dangerous in terms of operational consequences. The type of failures is, as a rule, already known. In diesel 5RD68 there are failures in the cylinders; in K9Z62/102E, failures in the cylinder covers; in 6DKRN 65/120 – 10, falures in the pistons and cylinders.

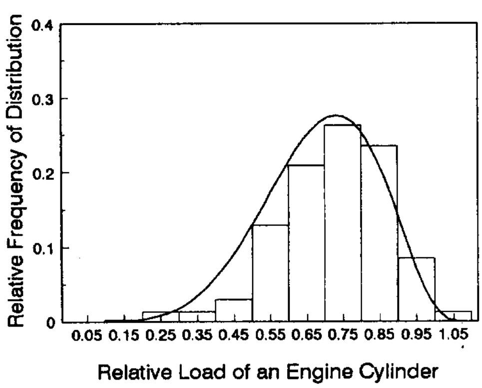
In order to evaluate the stresses and temperatures in engine parts, the method of finite elements was used. The initial data used boundary conditions of the third kind. The significance of pressure and temperature was defined by processing indicator cards, taken from the ship' s diesels. The processing of the indicator cards was done automatically with the help of a personal computer and a special device for processing the information. The error of the pressure ordinate' s reading did



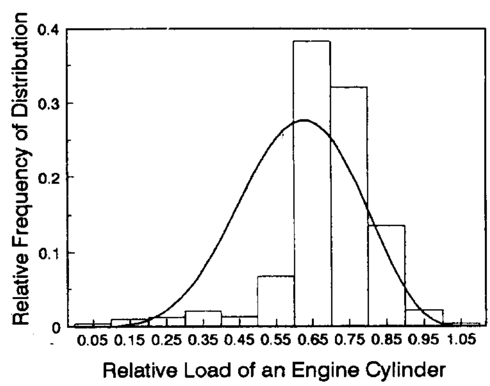
(a) m/s "Buhta Russkaya" type $\chi^2=2.25$



(b) m/s "Ohaneft" type $\chi^2=0.95$



(c) m/s "Tarhansk" type $\chi^2=1.3$



(d) m/s "Almazniy Bereg" type $\chi^2=1.04$

Fig. 1 Empirical and theoretical laws of distribution of cylinders of main engines:1-empirical;2-theoretical.

not exceed 0.1%.

A comparison of the results of the accounts of temperature fields of the cylinder and experimental measurements has shown that the divergence was not greater than 3.7%.

In order to determine the safe load for an engine the influence of a cylinder load to temperature and stress at critical points, a cylinder from the 5RD68 engine was investigated. The dependence of temperatures at critical points on the load of a cylinder is described by the equation:

$$T_{C\max}=A^{C}_{tm}(B^{C}_{tm})^{\overline{N}_C} \tag{7}$$

$$T_{C1PR}=A^{C}_{tPR}(B^{C}_{tPR})^{\overline{N}_C} \tag{8}$$

where $A^{C}_{tm}=105$, $B^{C}_{tm}=4.5$, $A^{C}_{tPR}=62.7$, $B^{C}_{tPR}=4.5$.

The relation of stress to a load in places where cracks arise in a cylinder is described by the equation:

$$\sigma_{\theta\max}=A^{C}_{\theta}+B^{C}_{\theta}\overline{N}_C \tag{9}$$

$$\sigma_y=A^{C}_{y}(B^{C}_{y})^{\overline{N}_C} \tag{10}$$

where $A^{C}_{\theta}=140$, $B^{C}_{\theta}=-400$, $A^{C}_{y}=0.165$, $B^{C}_{y}=546.8$.

The heaviest amount of stress on the cooled surface of the cylinder cover of the K9Z62/105E engine is also places where the cracks occur. The relation of maximum stress on the cooled surface to a load is described by the linear function:

$$\sigma_{\max}=A_{\sigma m}+B_{\sigma m}\ \overline{N}_C \tag{11}$$

where $A_{\sigma m}=-172$, $B_{\sigma m}=716$.

To calculate the probability of the non-failure of an engine part, it is necessary to find out the law of a load distribution (mechanical, thermal and etc.) and the bearing ability of the part.

Using the results of statistical experiments based on operational loads and computation or experimental methods to find the interrelations among the parameters, which lead to the failures of a given part, with the parameters, which describe a load, it is possible to formulate reception of such laws.

In order to deduce the law of the distribution of loads we shall use the theorem of the transformation of casual quantities:

$$g(y)=f(\Psi(y))\left|\frac{d(\Psi(y))}{dy}\right| \tag{12}$$

The generalized laws of distribution for stress and temperature, which lead to the failure of a part are described by the equations:

1) for models of interrelation of the type $y=A+BS$ – linear regression:

$$g(S)=\left|\frac{1}{B}\right|K_u\overline{N}^{\alpha}(1-\overline{N})^{\beta}\frac{1}{\sqrt{2\pi}\,\sigma_{\overline{N}_C}}\int_0^1\exp\left(-\frac{(\overline{N}_C-\overline{N})^2}{2\overline{\sigma}^2_{\overline{N}_C}}\right)d\,\overline{N}_C \tag{13}$$

where $\overline{N}=\frac{S-A}{B}$, $K_u=\frac{(\alpha+\beta+1)!}{\alpha!\beta!}$, $S=\sigma$ or $S=t$;

2) for models of interrelation of the type $y=AB^{n}+C$ – exponential regression:

$$g(S)=\left|\frac{1}{\ln B(S-C)}\right|K_u\overline{N}^{\alpha}(1-\overline{N})^{\beta}\frac{1}{\sqrt{2\pi}\,\overline{\sigma}_{\overline{N}_C}}\int_0^1\exp\left(-\frac{(\overline{N}_C-\overline{N})^2}{2\overline{\sigma}^2_{\overline{N}_C}}\right)d\,\overline{N}_C \tag{14}$$

where $\overline{N}=\frac{\ln(S-C)-\ln A}{\ln B}$, $K_u=\frac{(\alpha+\beta+1)!}{\alpha!\beta!}$, $S=\sigma$ or $S=t$;

The probable calculation of the load S and the bearing ability of part R are presented as casual quantities. For the parts of the cylinder piston assembly of the internal combustion engine they are independent. The probability of each part working is defined using the formula:

$$P=\int_{-\infty}^{\infty}f_R(R)\left[\int_{-\infty}^{\infty}f_S(S)\,dS\right]dR \tag{15}$$

3. Discussion and Results

Using the received formulas (13), (14) and taking into accounts the allowable stress by means of the distribution function, the following calculations were made (table 1).

As the table testifies the convergence of the

Table 1. Probabilities for non-failure of the cylinder and cylinder cover.

Part and kind of failure	Before modernization		After modernization	
	Calculation	Experiment	Calculation	Experiment
5RD68 engine clinder :				
vertical cracks	0.88	0.91	0.99	1..0
horizontal cracks	0.71	0.75	0.99	1.0
9Z62/105E engine cylinder cover: cracks on the part of cooling	0.60	0.65	0.99	1.0

account offered in this paper and the experiment is fairly close.

Mathematical models, therefore, are useful in describing the laws of the distribution of the parameters of the mechanical and thermal intensity of the parts of cylinder piston assembly in internal combustion engines.

4. Conclusions

Using these models, the optimum modes of operations of engines can be calculated, at a given reliability of its parts. The models also permit the calculation of the influence of the technical conditions of an engine on reliability of its functioning.

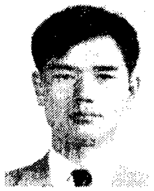
References

1) Efremov L.V., The engineering analysis of reliability, Leningrad, Sudostroenie, pp. 35-102, 1977.
2) The control of the efficiency of the use and setting consumption rate of a fuel for vessels and enterprises of the fishing fleet, Manual, Under general edition of SCHagin V.V., Kaliningrad. KTIFIandE, pp. 1-46, 1979.
3) Korn G., Korn T., The mathematicians directory for science officers and engineers, Moscow, Science, pp. 632-634, 1977.
4) Sobolenko A.N., Automated accounts of the strength of ship engines, St.-Petersburg, Sudostroenie, pp. 90-93, 1994.

저 자 소 개

아나톨리 쇼보랭코 (A. N. Sobolenko)
1949년 7월생. 1972년 극동수산대학교 졸업. 1976년 레닌그라드 주립조선대학교 대학원 졸업(박사). 1973년~현재 극동수산대학교 선박추진기계공학과 교수.

우종호(禹鍾鎬)
1954년 7월생. 1978년 경북대학교 공과대학 컴퓨터공학과 졸업. 1981년 경북대학교 대학원 전자공학과 졸업(석사). 1990년 동 대학원 졸업(박사). 1981년~현재 부경대학교 컴퓨터공학과 교수.



왕우경(王宇慶)
1958년 11월생. 1982년 부산수산대학 기관학과 졸업. 1991년 부산수산대학교 대학원 기관공학과 졸업(석사). 1992년~현재 여수대학교 실습선 교수. 당학회 회원.